A SURVEY OF VHF/UHF PROPAGATION MODES

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(Part 1)

Quentin Campbell first became interested in electronics while at school. After more than 20 years "thinking" about getting licensed, he was encouraged by colleagues to finally do something about it and obtained a G4 call in 1982. Always fascinated by telegraphy, he concentrated on reaching required proficiency in morse before attempting the RAE. Activity is now mainly centred on 144MHz cw dxing and investigating the application of digital techniques to certain vhf propagation modes. An Australian by nationality he is permanently resident in the UK.

Introduction

Most radio amateurs interested in vhf and uhf welcome "lift" conditions and those other quirks of nature that allow dramatic dx QSOs that sometimes span thousands of kilometres. At the same time they are often hard-pushed to give anything but the haziest description of what changes in the upper and lower atmosphere allow this to come about.

This article introduces the reader to the fascinating field of vhf/uhf propagation, and seeks to give him some insight into the underlying mechanisms. It is also a comprehensive survey of the current range of vhf/uhf propagation modes, and shows how many of these modes are exploited by amateurs as well as by some novel systems developed for use in military and professional applications.

We first look at the generally-understood model of line-of-sight propagation in an homogeneous atmosphere, and introduce some basic terms and concepts. We then look at deviations from this "simple" model; ie when irregularities and inhomogeneities occur in the lower atmosphere or when ionospheric effects are considered.

Some of these phenomena are very important from a communications engineering point of view, and in fact provide the only *reliable* means of long distance radio communications available today. They give rise to the regular propagation modes which include:

- Line-of-sight communications
- Tropospheric scatter
- Knife-edge diffraction
- Ionospheric scatter

Other phenomena are only short-lived and infrequent and therefore cannot be used for regular commercial communications, but can be exploited by the amateur to provide vhf communications at distances often spanning many thousands of kilometres. Some are man-made for scientific or military use. These are together called the anomalous propagation modes (also referred to as the irregular or abnormal modes) and include:

- Super-refraction and ducting in the troposphere
- Sporadic-E propagation
- Field-aligned scatter
- "Chaff" and needles

The first two are important because they can be major sources of interference to the regular propagation modes. The last two have special scientific or military uses.

These regular and anomalous propagation modes are dealt with here in an unorthodox way. Rather than categorizing them as either tropospheric or ionospheric modes, they are grouped according to the underlying mechanism involved. Thus the first group, and by far the most important, encompasses those modes that involve scattering of the radio waves due to irregularities in the transmission medium. The second group includes the strong but unstable propagation due to specific meteorological or ionospheric conditions that do not involve substantial scattering. Also included here are the enhanced propagation due to unusual geographical features and reflections from the moon.

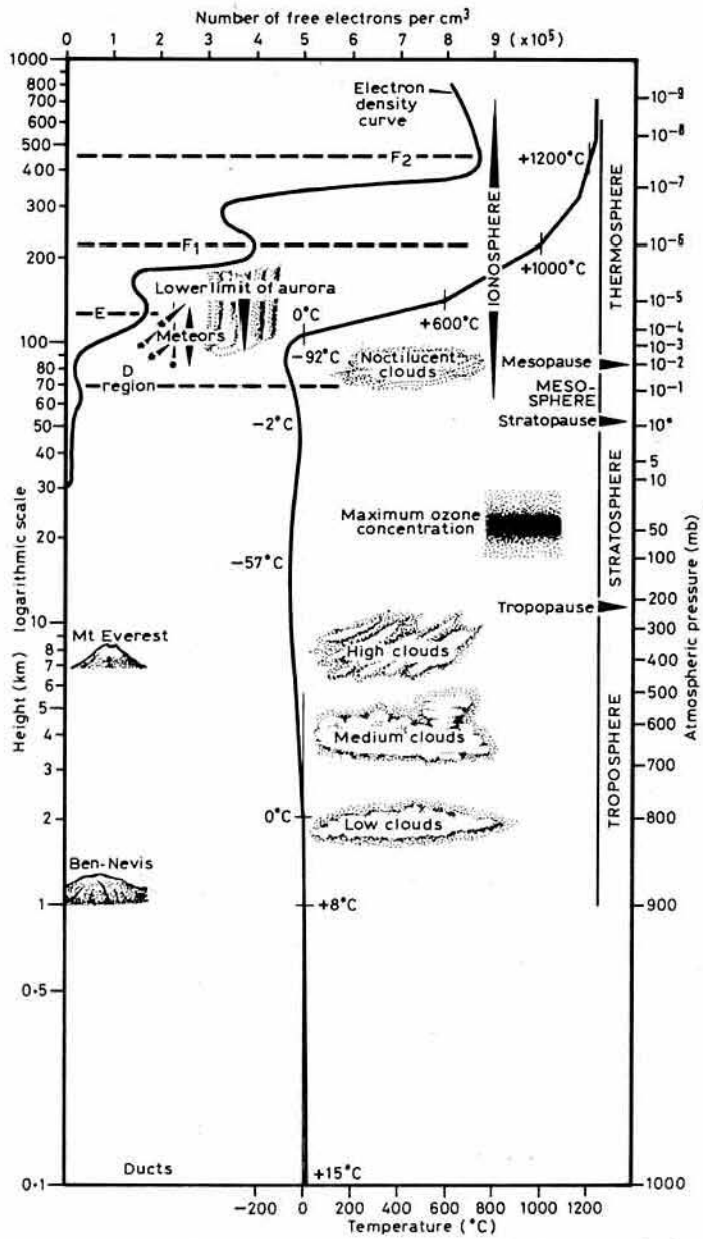

Fig 1. Some features of the earth's atmosphere. The height scale is logarithmic beginning at 100m asl. The equivalent pressure scale on the right is not regularly spaced because the relationship between pressure and height depends on temperature, which does not change uniformly with height (from *Radio Communication Handbook*, Vol 2)

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Line-of-sight propagation in the troposphere at vhf/uhf

The vhf band is usually defined as the frequency range 30 to 300MHz, and the uhf band as 300 to 3,000MHz (3GHz). The choice of these limits is purely arbitrary, although the lower limit of the vhf band is based on the observation that the maximum electron densities in the ionosphere are rarely sufficient to reflect radio waves on frequencies much above 30MHz except for short periods.

The most important mechanism affecting vhf/uhf propagation and performance has its origins in the troposphere, which is defined as the lower part of the atmosphere, in which the temperature decreases with altitude. It is limited on its upper boundary by the tropopause, a zone where the temperature remains more or less constant. The thickness of the troposphere varies, but is on average about 10km.

Changes in refractive index occur in the troposphere due to variations in density. On average, the refractive index of the troposphere decreases with altitude. A general consequence of this is that, in terms of geometric optics, radio waves do not propagate in straight lines. The radio waves will bend towards the region of highest refractive index. Thus, with a decrease of refractive index with height, the radio waves will bend towards the earth's surface and over the visual horizon. The result is a lengthening in the line-of-sight path.

However, Nature is never constant, and anomalies or irregularities in the troposphere as well as ionospheric effects cause interesting deviations from this simple definition of vhf/uhf propagation.

Non-line-of-sight propagation in the vhf/uhf region

It was often the discovery of unexpected signal propagation that led to the recognition and consequent investigation of the underlying phenomenon. Conversely, studies of the phenomenon have greatly helped to provide quantitative data that has been used by designers of communications systems. Sometimes the study of these phenomena has suggested man-made irregularities that might be created and utilized to further propagation studies or to provide more reliable propagation conditions.

These non-line-of-sight vhf/uhf propagation modes can be classed into two broad groups: scatter modes and non-scatter modes. As we shall see later, the scatter modes can be further usefully divided into man-made scatter conditions and naturally-occurring scatter phenomena.

Scatter modes of propagation at vhf/uhf

So far we have only looked at large-scale height gradient changes of refractive index in the troposphere and the way it can cause a bending of the path of a radio wave. If the refractive index gradient at a horizontal boundary between two large air masses is sufficiently abrupt compared with the radio wavelength it may cause partial reflection, in the optical sense, of incident radio energy. This is dealt with later under "Tropospheric ducting and reflection".

Small-scale variations of refractive index due to local pockets of differing density are also important. These have a scale too small for their effects to be treated adequately on a simple refraction basis. If these refractive index irregularities are of sufficient intensity they will scatter radio energy, and the amount and direction of this scattering will depend on the spatial distribution and the radio wavelength. It can be shown that those parts of the wave scattered in the forward direction maintain their "coherence" (ie, remain in the same phase) and thus add together to produce a strong wave. Those parts of the wave scattered in the other directions add together out of phase and thus their combination produces only a weak wave.

An analagous effect occurs in the ionosphere, but here the scattering mechanisms are collections of charged particles or other conducting media, such as copper needles, as we shall see later.

VHF/UHF scatter communications thus rely on reflection by forward scattering of the radio wave, caused by small irregularities and inhomogeneities in the propagation medium, rather than by the refractive effects of large-scale changes. Scatter systems work because the average intensity of these signals is sufficiently high to provide usable communications links. To ensure this, the communications system must do one of two things:

(i) Use high transmitting powers, sophisticated receivers and high-gain antennas as in troposcatter systems;

(ii) Adapt to the intermittent nature of the communications channel as in meteor-burst systems.

Most of these irregularities causing scatter involve quite small disturbances in the surrounding conditions. Two exceptions are the greatly-enhanced ionization of meteor trails and the highly conducting strips of "Chaff". Typical sources of the irregularities are:

(a) random inhomogeneities in the troposphere in which the refractive index differs from the mean value of surrounding areas;

(b) turbulent mixing of the electron density distributions in the D-region of the ionosphere;

(c) ionized trails due to the passage of meteors through the atmosphere; and

(d) spread-F phenomenon, particularly in equatorial regions.

The man-made scatter conditions are:

(a) "Chaff" and needles;

(b) Field-aligned scatter.

These irregularities and man-made scatter conditions give rise to the following recognized scatter modes of vhf/uhf radio wave propagation.

Ionospheric scatter propagation (ionoscatter)

The possibility that radio waves might be transmitted by scattering due to irregularities in the ionosphere was suggested as far back as 1913. Little interest seems to have been shown until high-frequency communications came into general use, when T L Eckersley began to investigate the possibility of E-region scattering of radio waves in 1932 [1, and refs therein]. More recent work has demonstrated a regular but weak scattering from irregularities in the D-region. These irregularities are produced by the action of turbulence, wind shear etc on the electron distribution in this region and result in corresponding fluctuations in refractive index [2].

Ionoscatter propagation requires that a strong, narrow, beam of radio waves be transmitted nearly horizontally to meet the ionosphere at a height of some 100km at a distance of about 1,000km from the transmitter. The frequency used must be high enough so that it can escape into space instead of being reflected, and a typical frequency might be 35MHz. These high frequencies are one factor that distinguish ionoscatter from conventional hf ionospheric reflection propagation. The ionospheric irregularities, of a size comparable to the wavelength used, scatter a small part of the wave in all directions, but with a preference for the forward direction. Using a sensitive receiver, this regular but weak forward scattering is useful for single-frequency communication in the 30 to 60MHz range over distances up to 2,000km.

The main advantage of ionoscatter propagation was thought to be its relative immunity from disruption by fadeouts, ionospheric storms and polar blackouts. This last phenomena, called polar cap absorption (pca), can lead to an almost complete break in communications in the polar regions. Long-lasting blackouts occur which are not associated with auroras (see "Auroral scatter propagation" later) or magnetic storms. They appear to be caused by the expulsion of high energy particles from solar flares on the visible hemisphere of the sun. The start of the pca event follows from one to several hours after the appearance of the flare and lasts about three days; however, it may be as short as one day and as long as 10 days. Strong ionization descends to an altitude of 70 or even 50km, causing extremely strong absorption of radio signals, particularly at hf. It is believed that pca events occur simultaneously at both poles [2, 22].

As the frequencies used in ionoscatter links are much higher than in conventional hf propagation, the radio waves are not unduly absorbed by the extra ionization that is present in the lower ionosphere during these events; and storm effects in the upper ionosphere are of little importance because the waves are scattered from lower down. Since the 'fifties, however, interest in ionoscatter systems seems to have diminished for two reasons. The main factor is its inefficiency, since high powers and large antenna systems are needed if reasonable circuit capacity is to be achieved. A secondary factor has been its disappointing performance in Arctic regions, where its immunity to blackouts from pca effects was less than expected. In spite of these problems Nato has continued to experiment with transportable and fixed systems using this mode [3].

However, under certain traffic conditions, the mode discussed next offers some useful operational advantages over ionoscatter systems.

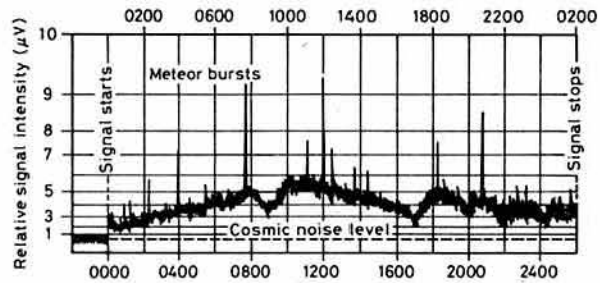


Fig 2. Ionospheric scatter signal level is low, punctuated by stronger signals reflected from meteor trails (from [25])

Meteor-burst propagation (meteor-scatter)

If you look at a tracing of the received signal on an ionoscatter link, it will show irregularly spaced bursts of appreciably higher signal strength, whose durations are of the order of one second. These are due to reflections from the ionized trails left by meteors as they pass through the earth's atmosphere in the region 80 to 120km high. Because of the intermittent nature and variable duration and strength of these signals, it is usual to refer to "meteor-burst" and to "meteor-burst-systems".

As would be expected, the variability of signal levels reflected from the ionized trails of meteors is much greater than the variability arising in ionoscatter systems. However, meteor trail signals are, on average, much stronger than the corresponding ionoscatter signals, although far fewer in number. Therefore, systems using meteor trails can operate at lower power levels and lower antenna gains than ionoscatter systems over the same route. The penalty which has to be paid is that reception is only intermittent with duty cycles that could be as low as one per cent; but if such a duty cycle can be tolerated, then a gain of some 20dB can be achieved with respect to the average equivalent ionoscatter case. This can result in a useful reduction in size, cost and complexity of the alternative meteor-burst system [4].

All this might seem surprising to the casual observer of the night sky who may see very few meteors streaking across the heavens. In fact, many thousands of millions of these trails are produced daily: only a very few of these meteors are large enough to leave a trail that can be seen by the naked eye. The ionized trail is the result of conversion of the kinetic energy of the meteor as it is slowed down by collisions with the molecules of the earth's atmosphere. The resulting ionization is distributed in the form of a long, thin column, typically 15–20km long, with the meteor at the head of it. The electron density per unit length of the trail is proportional to the mass of the meteor; the largest number of these are tiny particles less than one-fifth of a millimetre in diameter. Trails with electron densities in excess of 1×10^{13} electrons/m^3, produced by the larger particles, are termed "overdense" and can considerably modify the incident radio wave, owing to interaction between electrons in the trail. "Underdense" trails, on the other hand, provide scattered signals which are remarkably space- and time-coherent. This can provide an extremely high coherent bandwidth, with the instantaneous 3dB bandwidth being as high as 7MHz at an operating frequency of 30MHz [10].

A small fraction of meteors incident on the atmosphere occur in showers. Called shower meteors, these are due to groups of particles moving in well-defined orbits around the sun, and their arrival can thus be predicted. However, the vast majority of the total number of meteors entering our atmosphere are accounted for by sporadic meteors, which are particles moving in random orbits. The arrival rate is random, with a 4:1 variation between the maximum in August and the minimum in February. There is also a 4:1 diurnal variation, with a maximum in the morning and a minimum in the early evening, which is due to the earth's rotation.

During their brief existence, however, these ionized columns will reflect vhf radio waves, particularly in the frequency range 20 to 100MHz. Although few professional studies have been done on reflections at frequencies much above 100MHz, amateur meteor-scatter communication is common in the 144MHz band. Meteor trails therefore support what is essentially a satellite-type system where Nature continuously provides a multitude of unscheduled, short-lived, low-altitude passive satellites.

Meteor-burst propagation has been used, with varying success, in four operational communications systems. The random nature of these meteor trails means that they can be used only for rather special types of transmission. It is necessary to wait until a trail is formed in the proper position to reflect, and then to send the message very rapidly before the trail decays. The message is therefore inputted on a teleprinter keyboard and stored in electronic memory. A continuous probing signal is emitted: when a meteor trail is formed in the right place it reflects the probing signal strongly to the receiver, which is then caused to send a signal back to the transmitter where it initiates a rapid transmission of the stored message. If there are still more messages to be sent, it is transmitted when the next suitable trail is formed. This was the essential nature of the first meteor-burst system called Janet, a product of the Defence Board of Canada, which was developed in the late 'fifties. After extensive testing by Nato of a modified version of this system called Janet-B, they decided to develop their own approach. The resulting communications system was code-named Comet and became an operational Nato system in 1968.

Comet is capable of supporting up to eight 50-baud teleprinter channels in the 36 to 39MHz frequency range over distances up to 2,000km. This system uses a full-duplex technique; station "1" sends out a continuous probing signal on frequency "A" while listening for the probing signal from station "2" on frequency "B". Likewise, station "2" is sending out a continuous probing signal on frequency "B" while listening for station "1's" probing signal on frequency "A". When either station hears the other's probing signal, it transmits a section of any stored message it might be holding. In this way the information is transmitted over the circuit in both directions at an instantaneous rate of 2,000 bauds (using fsk with ±3kHz deviation) whenever a radio path is established by reflection from a meteor trail. The control of the flow of information is not based on an assessment of the signal strength as in the Janet system. Instead, it uses an error-detection scheme with automatic request for retransmission (ARQ) where, every time an error is detected at one or the other terminals, a repetition of the mutilated character is requested [4, 5, 6, 7, 8].

More recently, two non-military systems have been developed. The first of these networks, called Snotel (SNOwpack TELemetry), was set up for the Soil Conservation Service of the US Department of Agriculture. It consists of over 500 remote, unattended "data sites" which have instruments to measure the weight and volume of the snow pack and hence to determine its water content. Other instruments measure temperature, snow and rainfall. This data is digitized and stored in a buffer for later transmission. All the sensing instruments, microprocessor and communications gear at the remote site are powered by a single 12V gel accumulator. This is continuously charged by solar cells, and the power system is designed for a one-year maintenance-free duty cycle.

Two monitoring stations receive the data. Every day during the winter, the two monitoring stations poll each "data site" in turn. Transmission from the site takes about 100ms. If a contact is not successfully made on the first attempt, it is put on a list of sites to be contacted on the next hourly schedule. Within three hours, 90 per cent of the "data sites" will have responded, transmitting the stored environmental data as well as date, time and battery voltage. The purpose of this data collection system is to obtain a very accurate estimation of the amount of water that will be available from the mountain watersheds as the snow melts. Today, Snotel is the largest automatic data acquisition network of this sort in the world [9].

The second non-military network, developed by a Finnish company for remote sensing of weather data, is similar in operation to Snotel.

From a military communications point of view, some of the primary attractions of meteor-burst systems are their simplicity and inherent secrecy, the latter feature resulting from the restricted "footprint" of reflections from meteor trails. This arises because a communication link is established only during the brief interval when a meteor trail occurs with the proper geometric orientation with respect to the transmitter and receiver. The proper orientation is such that the angles of incidence and reflection in the transmitter–meteor–receiver path are equal. This geometric condition, known as specular reflection, is satisfied whenever the trail is tangent to one of a family of spheroids having the transmitter and receiver as foci. Due to this specular scattering requirement, signals propagating between a specific transmitter and receiver can normally be detected by an eavesdropping receiver only if the latter is located in an elliptically-bounded "footprint" in the vicinity of the intended receiver. For related reasons, meteor-burst systems also have a lowered vulnerability to jamming from beyond-the-horizon transmitters [10].

Obviously these characteristics are also of benefit to amateurs. The low probability of intercept and immunity to jamming means that many stations can use the same frequency with low probability of causing mutual interference. The simplicity of the transmitting equipment, and the modest power levels and antenna gains needed, means that useful data rates can be achieved at transmitter powers well within the limits of the amateur licence, and at costs well within the reach of most amateurs who already own a home microcomputer.

Auroral scatter propagation

Visible aurora arises when streams of electrons projected from the sun collide with the atoms or molecules of gas in the upper atmosphere. Due to the nature of the earth's magnetic field, these streams of electrons are deviated and concentrated in roughly circular rings around the poles known as the auroral zones.

These streams of electrons occur at times of unusual disturbances on the sun, when the expulsion of charged particles is more energetic and streams of mainly electrons and protons travel through the solar wind towards the earth. As they impinge on the earth's magnetosphere they alter its shape, giving rise to a sudden increase in the geomagnetic field at the ground: this is the first indication of a magnetic storm, and is most intense near the auroral zones. During the main phase of the storm, an increase in the magnetic field is noticed around the equator, and energetic particles also leave the magnetosphere and enter the ionosphere along the night side of the auroral oval. These excite the light of the aurora and increase the currents flowing in the ionosphere, particularly over the auroral zones. These strong currents, called the "auroral electrojet", may also influence the occurrence of one form of sporadic-E cloud (see "Sporadic-E propagation" later). The increase in the intensity of the light of the aurora

means that there is an increase in the ionization in the auroral zone. This ionospheric ionization, associated with magnetic storms, gives rise to radio wave reflection.

It is important to be clear about the distinction between visible aurora and radio aurora before dealing with auroral propagation phenomena. Visible aurora is a manifestation of atomic excitation and ionization in the form of visible and invisible radiation. Radio aurora, on the other hand, is made up of the electrons and ions separated during this ionization process. These charged particles form reflecting regions that tend to align themselves along the lines of geomagnetic latitude with very little extension in the transverse direction. These field-aligned irregularities (see also "Field-aligned scatter propagation (fas)" later) cause reflection and scattering of the radio wave, but they are aspect sensitive so the transmitter and receivers must be in the correct positions to be able to "see" the radio aurora. Thus, from a given position, one may observe visible aurora but not radio aurora. On the other hand, radio aurora may be observable during the day when visible aurora cannot be seen.

During auroral disturbances the zone of activity extends further from the polar regions than is normally the case. The average height from which the radio waves of powerful transmitters are scattered is in the E-layer at about 110km; for this reason it is sometimes called auroral-E. The field-aligned irregularities present during these storms may also cause reflection of the weaker amateur signals. The reflection of radio waves by sporadic-E clouds of auroral origin may also be important.

Auroras follow a seasonal pattern, peaking around March and September, although they may occur at any time. In the northern hemisphere the zone of maximum occurrence swings across northern Norway, Greenland and central Canada and back across Alaska, Siberia and European USSR. During periods of increased auroral activity, propagation on the 28, 50, 70 and 144MHz amateur bands generally shows two phases of activity, with two-way transmission paths favouring stations on similar latitudes, each beaming well north of the great-circle path between them. The activity then generally extends southward, often ceasing abruptly while the longest paths are open.

Auroral propagation seems to reach a peak around sundown or early evening, and again around 2am, and the further north a station is situated, the more frequently it will encounter auroral propagation. The propagation of signals is common at frequencies between 28 and 440MHz, and it is possible to communicate at distances up to 2,000km although ranges of several hundred kilometres are more common. East-west transmission paths are usually favoured. Characteristically, radio aurora imparts a rapid flutter to signals and an unmistakable tone caused by multi-path effects and doppler shift. This flutter, which is not constant, may vary between 50 and 2,000Hz, and makes cw the preferred mode for communications, as most ssb signals can be difficult to read unless signal levels are very strong. The higher one goes in frequency to work during an auroral opening, the longer the doppler flutter becomes. To try to overcome this, a stronger ssb signal is needed in order to be readable.

During all this increased vhf activity, however, auroral disturbances can be causing severe disruption to hf communications. This disruption is due to the almost total absorption of hf radio waves that can occur in the D-region near the auroral zone during magnetic storms. For this reason these hf radio blackouts are often referred to as auroral absorption or auroral blackout. (This is not to be confused with polar cap absorption.)

Although it will be poor consolation for the amateur hf devotee, the monitoring of the characteristic auroral-flutter distortion on signals in the 2 to 5MHz range may be evidence that vhf auroral propagation could soon be possible.

Tropospheric scatter propagation (troposcatter)

During the second world war, it had been observed that there were many incidents of radar signals being reflected from objects well beyond the radio horizon. These cases could be explained at the time by super-refraction and ducting in the atmosphere (see below). However, after the war experiments were made showing that beyond-the-horizon signal levels existed which, though not as powerful as ducted signals, were well in excess of the levels that could be accounted for by gradual refraction. These signals were explained as the effect of scattering from irregularities which exist in the troposphere.

Viewed more critically, the troposphere is not homogeneous; its refractive index varies randomly from one point to another around the mean value determined by altitude. This produces two kinds of result:

(i) Strong but unstable propagation, due to specific meteorological conditions of short duration, which cannot be used for regular communications. These give rise to super-refraction and ducting which are dealt with later.

(ii) Weak but permanent propagation, due to ever-present small irregularities causing tropospheric scattering. The result of this scatter refraction is a signal illumination of the ground well beyond the horizon. The average intensity of these signals, however, is sufficiently high to provide consistently-usable communication links over large distances.

The mechanism of a tropospheric scatter circuit is as illustrated in Fig 3. Both ends of the circuit are equipped with high-gain, highly-directive antennas. The transmitter emits a high power density into the narrow cone formed by the antenna beam. The receiver collects the energy scattered by the volume that is common to the beams of both antennas.

Attenuation is less when the altitude, h, of the common volume, as well as the angle, Θ, between both beams, are smaller. For a given distance, this will be achieved if the horizons of both antennas are completely clear and their beams are tangential to the ground. The rapid increase in attenuation on a path when the antenna beams are directed well above the horizontal, occurs because the common volume is at a height where the refractive index fluctuations that cause scatter are less intense, and because the effective common scattering volume is also reduced.

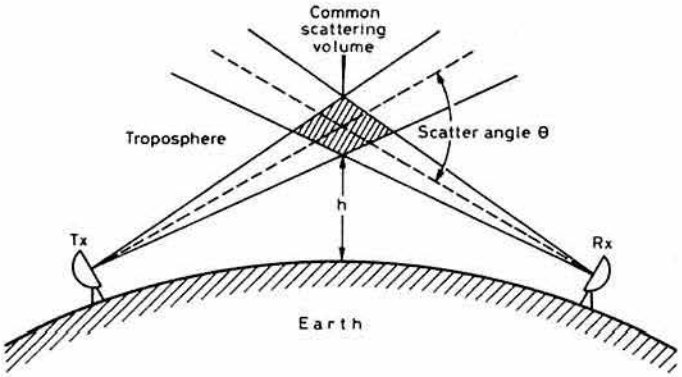


Fig 3. The forward scatter mechanism involves a large transmission loss and requires high gain, narrow beam attennas at both ends of the circuit. The scatter angle is kept as small as possible by careful choice of antenna sites (from [25])

The available bandwidth is related to the antenna's radiation pattern. In simple terms, if the antenna has a broad beam, the paths of the various rays through the common volume will be very different in length and therefore in transmit time. In this case, it is only possible to transmit signals varying so slowly that the difference in transmit times for the different paths becomes insignificant; this means that only a narrowband signal can be reliably received. To receive wideband signals reliably, it is necessary to use antenna having such a narrow beam that the difference in transmit time for the various paths through the common volume remains small in relation to the reciprocal of the desired bandwidth.

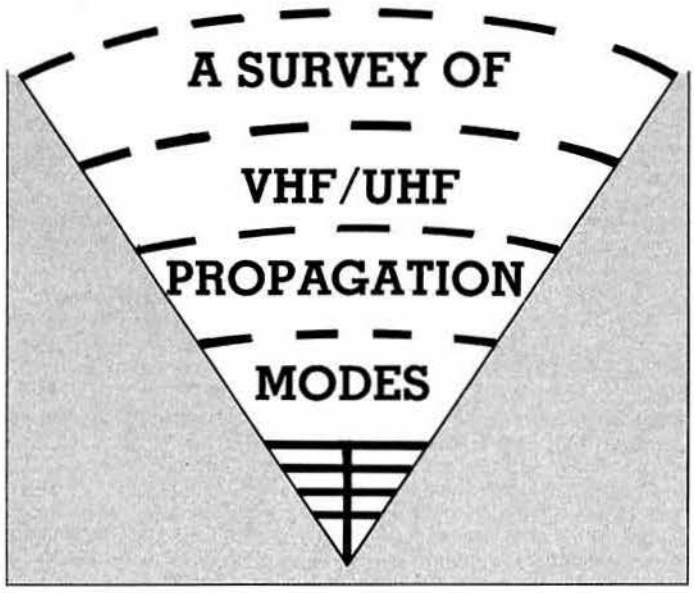
Obviously, tropospheric scattering exists even when the antennas are in line of sight. In this case the scattered field is, relatively speaking, usually much weaker than the main field, so its effects are swamped by the latter. During periods of strong fading, however, the scattered field is less affected and the received signal can show characteristics similar to those of a troposcatter link.

Troposcatter links may be established over distances up to 1,000km for the transmission of small-capacity multiplex-telephony signals without relay stations, and over medium-distance ranges of 200 to 300km for the transmission of a large number of telephony or tv channels. As signal fading is normally severe and the losses due to the forward-scattering mechanism involved are large, troposcatter systems require high-power transmitters, high-gain antennas, sensitive receivers and usually some means of diversity reception to overcome signal fading. High-gain antennas require large reflecting surfaces, so the lower frequency limit to practical operation has been about 200MHz. The upper frequency limit of about 5GHz is set by the increase in attenuation with frequency and attenuation due to rain etc which becomes appreciable on long paths. Since the effect of the scatter angle between the receiving and the transmitting beam antennas is significant, it is kept to a minimum by choosing transmitting and receiving sites so as to have an unobstructed view of the horizon.

Due to the equipment and power requirements described above, this mode is not normally open to amateurs. However, it is possible for two well-sited stations equipped for eme operation (see "Earth-moon-earth propagation" later) to establish regular communication at vhf over hundreds of kilometres using tropospheric scatter.

Judged simply on the number of operational circuits, troposcatter is by far the most important form of scatter communications.

TO BE CONCLUDED



Quentin Campbell, G4OEU*

(Part 2)

Transequatorial scatter propagation (tep)

American amateur radio operators discovered in 1947 that when sunpsot activity was high they could communicate on the 50MHz band over long north-south paths across the magnetic equator. What made this surprising was that this frequency was well above the maximum usable frequency (muf) for the distances involved. Tests since 1947 have established the base of the F2 layer as the scattering centre for this mode.

TEP, also called Equatorial F-scatter propagation, is, in general, dependent on high solar flux, and appears to be most prevalent around the autumnal equinox. However, at frequencies below about 50MHz, tep can persist for long periods during the day over some paths even when sunspot activity is low. This daytime enhancement is probably related to the regions of high electron concentration that form along the magnetic equator during the afternoon and early evening [2].

The mode is used by amateurs mostly on 50MHz paths between North and South America, Africa and Europe and Australia and Japan. In a recent paper [11] the authors categorize this propagation as "F" or "afternoon" type tep, and distinguish it from "pure" or "evening" tep which is a form of F-scatter associated with a geophysical feature known as equatorial spread F. This latter form of tep, they believe, is responsible for propagating signals at frequencies as high as 144MHz over distances of up to 8,000km between Greece and Southern Africa. But there is an unwanted side to tep however; this is the occurrence of rapid flutter fading and "chopping up" of voice modulation during the 2 or 3 hours after sunset which can make voice communication channels that cross this equatorial sector virtually unusable.

Chaff and Needles

This is one of the two man-made scatter phenomena; the other is field aligned scatter (fas), which is dealt with next.

Needles are a special version of Chaff in which extremely thin dipoles could be spread in two 8,000km altitude belts, one polar and one equatorial, to give continuous, worldwide coverage which is immune to physical attack and direct jamming. Other advantages of this orbiting dipole communications technique are the high reliability which is inherent, since all the electronic equipment is on the ground, the frequencies are in the microwave region (1 to 10GHz) and both the nature of the dipole belt and the transmission methods to be used (high-bandwidth, spread spectrum as well as multiple independent circuits) provide a high degree of resistance to interference. Low antenna tracking rates and absence of satellite "handover" permit the simplification of ground and tracking systems [12].

This idea is based on the results of the "West Ford" project where, in 1963, about 20kg of copper in the form of some 480 million hair-like fibres, each 1·8cm long, were released by satellite to form a dipole belt around the earth with an average altitude of about 3,700km and a near polar orbit. Very soon afterwards, transcontinental orbital scatter communications were made with teleprinter, voice and high-speed digital data transmission using two 18m dishes operating at a frequency of about 8GHz. However, this experiment was deliberately designed to limit both the density and the lifetime of the belt, but provided much interesting data and confirmation of theoretical predictions which were of benefit to radio physicists and radio system designers alike. One particular contribution this project made was a concentration of effort into overcoming the problems of multipath effects. The problem is particularly acute in this form of scatter communications because the dipoles in the scattering volume result in a spread of propagation delays due to the spread of the dipoles in space and a spread of doppler shifts due to the spread of dipole velocities.

The "West Ford" experiment was not without its critics, particularly among the optical and radio astronomers. In 1960, the Royal Astronomical Society passed a resolution which viewed "West Ford" with the greatest concern. Many other national scientific bodies also expressed their unease about the project. The general feeling seemed to be that although most scientists could accept the estimates that this first belt would not prove harmful, they were fearful of future denser belts if the initial experiment proved successful. The whole issue came to a head at the 11th General Assembly of the International Astronomical Union, held in Berkeley in August 1961, where it was resolved to work with the "West Ford" project but to stress the danger of a long-lived dipole belt to astronomy [13, 14].

While Chaff is normally used to deceive enemy radar, it can also be used to provide a temporary scatter system of communications. A requirement of this nature could arise in military communications if the middle terminal of two troposcatter links in tandem were out of action. Chaff could be dropped in the common volume by plane or rocket, and the signals would then overpass this terminal up to a distance of perhaps 600km.

For use between mobile stations, a suggested system would use 1kW of power at 3GHz with 1m dishes. Then a rocket releasing a payload of 4kg of Chaff at 30,000ft could provide a single fm voice channel for about 1h while the two stations tracked the cloud of Chaff as it fell to about 7,000ft. A number of tests involving aircraft and missile dispensers have been carried out to validate these techniques [4, 15].

Field-aligned scatter propagation (fas)

Field-aligned scatter (fas), on the other hand, relies on increasing the electron temperature of the F-layer by turning on a heating transmitter.

Some 50 years ago it was suggested that the lower ionosphere could be heated by the use of a powerful transmitter operating at a frequency near the natural rotational frequency of electrons in the earth's magnetic field (often called the "gyro frequency" or "plasma frequency" and has a value of about 1·4MHz). However, there are too many practical difficulties to be able to experiment effectively at this frequency but, by making use of deviation absorption to cause heating, a much higher frequency can be used. This frequency ranges from about 0·5 to 1·0 of the maximum critical frequency of the ionosphere.

The first observed, deliberate, modification of the F-region was produced in April 1970 by the US Department of Commerce's, Platteville, Colorado, high-power transmitter facility. Since then many unexpected physical phenomena have been observed, and new understanding has been gained in this area of plasma physics because of the ability to carry out controlled modifications of the ionosphere. Of more immediate interest to us is that it has been shown that the modified ionospheric region acts as a significant radio scatterer to radio frequencies as high as uhf. It has also been shown that a usefully large scatterer in the ionosphere can be produced with powers as low as 200kW and simple dipole antennas.

From a communications point of view, the most important change that this causes is the formation of field aligned irregularities which consist of "filaments" of increased ionization aligned with the earth's magnetic field. Although such field-aligned scatterers can provide communications over ranges in excess of 2,000km, it is highly aspect-sensitive, so that communication via fas is limited to certain zones. The main operational difficulty is that of managing the frequency of the heater transmitter so as to maintain a continuous cloud of field-aligned scatterers at the altitude appropriate for the path geometry and prevailing ionospheric refraction conditions. A practical communications system would therefore need to use a judicious mixture of ionospheric predictions and soundings coupled with real-time computer control of the heating transmitter [16, 17, 18].

The Platteville facility is interesting in itself. It consists of two 10-element ring-arrays, one for the frequency range 2·7 to 3·5MHz, the other for 4·5 to 10MHz, along with a 1·9MW transmitter. This comprises 10 identical amplifier channels each putting out about 200kW which can be switched to an element of either antenna array. Each amplifier is tunable from 2·7 to

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25MHz, and tuning can be altered at a rate of about 600kHz/min while delivering almost full power. There is also a capability for reducing power in steps of 3dB down to −18dB of full power, and many different forms of modulation can be employed to suit different experimental conditions.

One aspect of the planning and construction of this facility demonstrates that both amateur and professional radio engineers have some unexpected problems in common and tackle them in a like manner. It seems that when the request for funding was submitted to Congress for approval, the designers were able to keep the estimate acceptably low by some judicious home-brewing and purchasing of surplus parts; the high-voltage power supply (3MW) was obtained from a surplus ballistic missile early warning system (bmews) transmitter, while the 5km of 50Ω coaxial transmission line needed was built in their own workshops from aluminium irrigation pipe with Teflon sleeves and spacers. They quote, with evident satisfaction, figures for the performance of a 366m length of this containing no less than 23 right-angle elbows which had a vswr of 1·07 over the frequency range 5 to 30MHz. A 30m length has an attenuation of only 0·02dB measured at 16MHz. These figures were only slightly higher than those for conventional 50Ω rigid copper line, while the power handling capacity was about the same [19].

The main use of Needles, Chaff and fas seem to be in military applications, where the latter two have the added advantage that they can be created at short notice.

Non-scatter modes of propagation at vhf

Most of the modes described here are too unstable and infrequent to provide regular communications. However, they include the modes encountered by amateurs during "lift" conditions, and thus an understanding of the underlying phenomena can help in their exploitation as well as explain why they cause such serious problems to non-amateur communications and to radar.

The irregularities giving rise to these modes includes:

(*a*) stratification of air masses in the troposphere giving rise to large changes in refractive index with height; and

(*b*) sporadic appearance of highly-ionized regions in the E-layer.

Also grouped under non-scatter modes, but able to provide more regular propagation, are:

(*a*) diffraction caused by sharply-edged ridges and mountains in the path of the radio wave; and

(*b*) signals reflected off the surface of the moon.

Super-refraction, ducting and reflection in the troposphere

One of the most important parameters in the influence of the troposphere on radio wave propagation is the large-scale variation of refractive-index with height. Variation in the horizontal direction is negligible by comparison. Such localized changes of refractive index with height cause reflection from elevated layers and ducting.

Changes in refractive index, n, of only a few parts in a million can have a significant effect on radio waves, and as values are so near to unity (typically 1·00035) it is usually more convenient to work in parts per million above unity, N; ie we subtract 1 from the refractive index value, n, and then multiply the difference by one million. In mathematical terms:

$$N = (n - 1) \times 10^6$$

which is, strictly speaking, the refractivity, but is more usually referred to as refractive index or N-units. Interested readers are referred to the RSGB's *VHF-UHF Manual* [20] for a more detailed discussion of radio refractive index and its measurement in air.

The degree of radio wave bending which results from refractive index changes can be assessed by calculating the decrease over unit distance. In practice, the measured median of the mean refractive index gradient in the first kilometre above ground in most temperate regions is about −40N-units/km. That is to say, in the UK there is a decrease in refractive index from the ground upwards of about 40 N-units in the first 1,000m of the atmosphere.

It is still possible to represent this refracted radio wave as straight-line propagation by a geometrical transformation to produce a model for which straight rays propagate above a "modified" earth of effective earth radius. When the refractive index gradient may be assumed to be constant over a considerable height interval, it can be shown that the effective earth radius is normally greater than the true earth radius. The ratio of the two is referred to as the effective earth radius factor, k. A mean refractive index gradient near the ground of about −40N-units/km gives a value of $k = 4/3$; ie effective earth radius is equal to the normal earth radius, a (a = 6,400km) multiplied by 4/3 which works out to be about 8,500km. For this reason it is common practice for radio system designers to use a 4/3 earth radius when drawing to scale the progress of rays (radio waves) from a transmitter. The special case when the ray curvature is the same as the earth curvature occurs when the refractive index gradient is equal to $1/a$; ie, this gradient is −157N-units/km. When the gradient is more negative than −157N-units/km the ray bending is towards the earth's surface.

By way of naming convention, if the ray is bent downwards less than the normal, it is said to be subrefracted (refractive index gradient is less negative than −40N-units/km). If the ray is bent downwards more than the normal, it is said to be superrefracted (refractive index gradient is more negative than −40N-units/km). If the ray is bent downwards so as to have a radius less than that of the earth, the possibility of ducting occurs (refractive index gradient is more negative than −157N-units/km).

If the boundary between two large horizontal masses of air is sharply defined, partial reflection may also take place for radio waves striking the boundary at grazing angles. The most common cause of this sharply-defined layering is temperature inversion. Normally, the temperature of the lower atmosphere decreases on average by 1°C for each 150m of altitude. When this rate is decreased for any reason, a temperature inversion is said to exist. Temperature inversions also cause a layering of refractive index profiles, and are often linked by many amateurs with periods of high pressure. The reason that there is any correlation is that high pressure generally indicates the presence of an anticyclone and settled weather conditions. This favours the formation of subsidence inversion which is caused by a mass of warm air cooling then slowly descending and producing a distinct boundary with the slightly colder air near the earth's surface. This type of inversion layer may last for several days. Other types of temperature inversion are the formation of dynamic inversion, in which a warm air mass overruns a colder mass, and the nocturnal inversion, brought about by the rapid cooling of surface air after sunset. These latter forms of inversion layers are usually short-lived, as convective activity at the ground heats up and destroys the stable layer. Best conditions often occur in the evening and just before sunrise. Poorest conditions are generally around midday when the atmosphere is relatively stable and convective activity is reaching a peak.

Whether a horizontally-stratified refractive index gradient more negative than −157N-units/km will cause reflection or ducting depends largely on the radio wavelength. Such a gradient might have inadequate vertical extent to cause ducting of vhf waves but adequate refractive index change at the boundary to cause reflection. For this reason ducting is more important in the uhf region, while reflection is more important at vhf.

Ducts or tropospheric ducting occurs when the refractive index decreases sharply with height over a large horizontal layer of stable air and radio waves are trapped as in a waveguide and experience low-loss propagation over long distances. Simple ducts occur in the type of temperature inversion where a warm air mass comes over a cold surface, such as the sea or frosty ground; the air is cooled from below, so that its lowest parts are denser and hence have a higher refractive index. This system is stable, so that normal turbulent mixing of air does not occur, and near the earth's surface the temperature increases with height. In this region the rate of change of refractive index can decrease rapidly, and if the gradient exceeds −157N-units/km then ducting occurs. Another important type of duct results from the type of layering where, for example, a warm air mass comes over a cooler mass so that a temperature inversion occurs at some distance above the ground. In this case the duct may not extend to the ground and it is then called an elevated duct.

As indicated above, two conditions are necessary for radio-wave ducting to occur. The first condition is that the refractive index gradient shall be equal to or more negative than −157N-units/km so that the radio waves must remain close to the earth's surface. The second necessary condition is that this gradient should be maintained over a height of many wavelengths. Ducts, therefore, can be likened to metallic waveguides, and in the same way have a wavelength cut-off above which radio waves will not propagate. Since the duct thickness is not limited sharply by a metallic surface but rather by zones where the refractive index gradient varies gradually, the cut-off is not sudden. A simple relationship between duct thickness and maximum wavelength to be propagated exists. By way of example, a typical duct near the ground 25m deep and refractive index change of −400N-units/km gives a computed cut-off wavelength of 0·15m. This gives a minimum frequency that can be propagated in this duct of 2GHz. A duct with the same refractive index gradient would have to extend well over 100m to propagate a wavelength of 2m. Normal duct thicknesses are such that complete trapping occurs mainly at shf (3 to 30GHz) and only in extreme conditions does complete trapping occur at vhf [21,22,23,24].

Due to the nature of reflections within the duct, skip-zones or "shadows" [21] can be created where signal strength is very low. Because the radio waves are trapped within the duct, there is a region above the duct that is shadowed from the radio waves within. However, the duct will

normally be "leaky", and some energy will steadily pass out of the top of the duct and into this shadow region. This adds to the transmission loss within the duct. A consequence of this leakage is that the field strength just above the duct at a distance well beyond the normal horizon may be higher than were the duct not present, and, by reciprocity, the signal level within the duct would be higher than normal even if the transmitter were just outside the duct. The shadow effect may also lead to much lower signal strength above the duct top if the transmitter is within the duct, or much lower signal strength within the duct if the transmitter is above. Both these factors have practical significance for troposcatter radio links and S- and X-band radar. For instance, if a sea-area-surveillance radar is placed on a cliff top to obtain long-distance coverage in normal conditions, a low-level duct may considerably reduce the echoes from relatively close objects due to the shadow effect, but enhance echoes from far beyond the normal horizon by duct leakage. By contrast, fire control radars, which usually operate with elevation angles greater than the limiting (or trapping) angle of the duct, will not be affected.

A quiet atmosphere, with just a gentle breeze to allow warm, moist air close to the ground to mix with that slightly higher up, is essential for the appearance of ducts, and they are mostly encountered across water or deserts. In mountainous areas, strong atmospheric turbulence and upward motion of air mitigate against the establishment of ducts. Ground-based ducts may also be formed by an unusually-rapid decrease of water vapour with height, as well as by an increase in temperature with height (inversion), or both effects together. Two causes which are associated with large bodies of water are evaporation and advection [21]. Evaporation of water vapour from the surface of the sea may cause a zone of high humidity (ie high refractive index) below a region of drier air. Such ducts are particularly likely to occur in the afternoon due to prolonged solar heating. Over tropical seas the high humidity existing near the surface produces almost permanent ducts which may contain a change of more than 400N-units. This sort of ducting is probably responsible for propagating amateur communications between California and Hawaii and between Brazil and Africa, where the paths can exceed 4,500km in length [25]. Advection, the movement of one air type over another, may cause hot dry air (from the land) to be blown over cold wet air, again producing a region of low refractive index above a region of high refractive index. This is most marked at evening with the onset of a land breeze.

Ducting and its related phenomena cannot provide a sufficiently reliable mode for professional communications purposes. While amateurs may welcome the effects of the unpredictable long-distance propagation made possible by ducting, super-refraction and tropospheric reflection, professional radio engineers view it as anomalous propagation and a serious problem. It gives rise to co-channel interference, which is particularly acute in the case of terrestial fixed-point services (eg interference between uhf tv transmitters) and in earth-space services at shf. The latter service suffers because the earth stations transmit unusually high powers and receive unusually weak signals. Any coupling medium within the earth-space beam can cause scattering of energy from the powerful transmission, but may more seriously cause interference to the sensitive receiver. Alternatively, tropospheric reflection and ducting may cause high interference levels by way of the earth-station antenna side lobes. The military don't like it for the additional reasons that it gives rise to random undesirable reception and leads to errors in radar and direction finding.

"Knife-edge" diffraction propagation and obstacle gain

If the antennas at the terminals of a line-of-sight path are so low that parts of the path pass close to the surface of the earth, the transmission loss due to diffraction effects will be well in excess of the free-space value even if the path is not directly obstructed. This loss is usually taken to be 6dB on the assumption that in the grazing condition, half of the wavefront—and so half of the field—is obstructed by the diffracting obstacle.

By ensuring that at least 55 per cent of the first Fresnel zone around a radio path is completely free of obstructions, this 6dB diffraction loss can be avoided. Allowing for any additional clearance, generally gives little further benefit. However, the atmospheric refraction varies with time, and any temporary subrefraction will have the same effect as increasing the height of any objects that might obstruct the path. For this reason it is usual practice to ensure that 60 per cent clearance occurs for an effective earth radius factor, k, less than unity to minimize subrefractive diffraction fading. This diffractive fading is the process most likely to determine the limit of service area coverage for amateur vhf/uhf fixed and mobile radio.

Where a radio path between two terminals is partially obstructed by an obstacle, some energy from the wave front is diffracted into the shadow region of the obstacle. In practice, the diffraction effect will be complicated by the shape of the obstacle and by the effects of the atmosphere, but a simplifying model can be used. For the case of a radio link with a very pronounced ridge of hills running across the line between the transmitter and receiver, this idealized model, known as "knife-edge" diffraction, is a well-established means of calculating diffraction losses relative to the free-space loss. This technique can be extended to propagation over multiple knife-edges. Account must also be taken of hill-top rounding, which can reduce the diffractive effect.

Diffractive effects give rise to the interesting notion of "obstacle gain". This is produced by a large obstacle visible from both ends of a diffraction path between two stations. This gain is the difference between the attenuation over a radio path having such an obstacle, and the usually greater attenuation that there would have been in the absence of any such obstacle. It may occur when a high-loss path is transferred into a single knife-edge diffraction path with less loss. This can produce a reliable radio link but, since diffraction losses are normally large, metallic surfaces may be placed on top of the ridge to aid diffraction/reflection of energy to and from the remote station when it is essential to operate such a path without an active repeater.

It can also happen that an obstacle in the shadow of a diffracting edge may, by double diffraction, cause the received power level in its own shadow to be as much as 15dB greater than if it were not there. A useful consequence of all these effects may be that moving to a site behind a sharp-topped ridge will produce an enhanced signal for a mobile or portable station [21].

A practical examination of the effect of knife-edge diffraction and obstacle gain on amateur transmissions can be found in "The Snowdon effect—an interesting case of vhf propagation", J David Last, GW3MZY, *Rad Com*, February 1983, pp136-8.

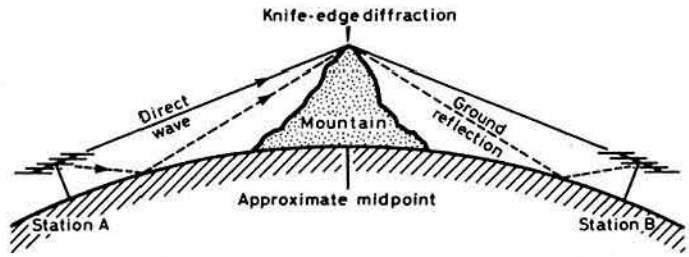

Fig 4. A ridge of hills or mountains may exhibit diffraction of a vhf radio wave travelling over the crest. An obstacle gain of as much as 15dB may be realized when transmitting and receiving sites are optimized for maximum diffraction (from [25])

Sporadic-E propagation

At about the height of the E-layer, highly-ionized clouds are randomly and sporadically formed. These clouds are of limited extent, consisting of horizontal sheets about 1km thick with a radius of between 100 and 2,000km at heights ranging from 90 to over 120km. The clouds do not behave consistently; they last for no more than a few hours at a time, but their lifetime can be much shorter; they vary in intensity and, whereas some will move over many hundreds of kilometres, others appear to remain stationary. Because of their transient nature and their altitude, they are called sporadic-E clouds and to differentiate them from other E-layer phenomena these clouds are designated "Es".

Close to the equator, Es clouds are essentially daytime phenomenon with little seasonal variation. On the other hand, in the auroral zone, Es is most prevalent during the night hours, but again there is little seasonal variation. In the temperate mid-latitudes, between approximately 6° and 60° latitude north and south, the maximum frequency reflected by the Es is less than elsewhere, and the occurrence is subject to daily and seasonal variations.

The ionized layers of auroral Es is probably caused by the precipitation of charged particles triggered by disturbances of the sun, as described earlier. The mechanism for the formation of temperate zone Es is believed to be wind shear; no extra ionization occurs as in the auroral zone Es, but rather the ionization normally present is redistributed and compressed into a ledge of high density. This is believed to occur through the action of neutral winds of high velocity, flowing in opposite directions at slightly different altitudes, producing shears. In the presence of a geomagnetic field, the ions are collected at a particular altitude forming a thin dense layer.

The occurrence rate of Es propagation over a given path is very sensitive to frequency. Propagation by Es at uhf is very doubtful, but as we move down in frequency from 144 to 28MHz, there are more events and they are of longer duration. The probability of a 144MHz opening is only about three to four per cent of the occurrence of 50MHz openings. However, signal strength observed over the vhf range does not appear to be frequency dependent [26]. Normal one-hop, single-cloud, Es dx is limited to about

Table 1

Band	Path loss (1)	Transmitter output power needed (2)	Antenna gain and dish diameter (3)	Comments (4)
144MHz	252dB	750W	20dB 4 × long Yagis 20dB 30ft dish	(a) Yagi arrays generally preferred, since you need 30ft dish to get same gain as four Yagis, but some stations use 8 or 16 Yagi arrays. Polarization mismatch can be a serious problem with these fixed polarization arrays. (b) Receiver noise level limited by higher sky noise temperature at this frequency. A noise figure of about 2dB is the best that can be expected. The noise picked up by the antenna may swamp the weak eme signal.
432MHz	262dB	750W	20dB 4 × long Yagis 20dB 13ft dish 25dB 8 × long Yagis 25dB 20ft dish	(a) Yagi arrays and dishes seem to be equally popular but with some arrays using up to 24 long Yagis. Losses in phasing harness etc can be high. (b) Possible to achieve a receiver noise level of about 1dB which is a noise temperature of 75°K. This is about the level of sky noise at 432MHz.
1,296MHz	272dB	400W	25dB 6·5ft dish 32dB 13ft dish	(a) Dishes normally used, as 32 or more Yagis needed to get sufficient gain and losses in phasing harness are too high. Circular polarization is standard. (b) More difficult and expensive to construct low noise receivers. However, sky noise temperature lower than at 432MHz.
		100W	35dB 20ft dish	(c) Suckling [27] reports that eme operation can be successful at this output power but antenna needs to have sufficient gain (at very least 6·5ft diameter).

Notes accompanying column headings
(1) The figure is for the isotropic loss; ie, antenna at both stations assumed to be isotropic radiators. See *VHF/UHF Manual* 3rd ed, pp9.13.
(2) The output power stated may be in excess of the UK amateur licence conditions. Home Office approval will need to be sought to run these powers.
(3) One or more stages of low noise preamplification are normally used. These are based on GaAsfets and are preferably situated at the base of the antenna.
(4) To achieve the necessary selectivity and sensitivity, the normal practice is to convert/transvert to hf after the preamplification stage. This is because received noise power is proportional to receiver passband width, and until recently few vhf/uhf receivers had sufficiently narrow filter passbands.

2,000km but, during the summer months, multiple clouds are common and most propagation is via more than one cloud. With the right distribution, distances of up to 4,000km or more are possible over land. This makes it a popular mode of communication for amateurs on the vhf bands, as it calls for no special station equipment, although a reasonable level of operating skill and a good deal of luck are needed.

Earth-moon-earth propagation (eme or moonbounce)

American radio amateurs began experimenting with moonbounce communications in about 1953. This mode of communication uses the surface of the moon as a passive reflector of radio signals, and allows communication on earth between any two stations that can observe the moon at the same time. Thus it is possible to communicate at vhf/uhf between stations at almost opposite sides of the earth. The mode does not rely on freak enhancements to propagation but does require equipment that is a little more sophisticated than the typical amateur vhf/uhf equipment that is commercially available.

The eme path length varies from about 712,000km to a maximum of 814,000km for a round-trip signal. This variation arises because the moon rotates around the earth in a slightly elliptical orbit, with the distance between the two varying on a 28-day cycle. The moon subtends an angle of only 0·5° as viewed from the earth, and reflects only about seven per cent of the vhf/uhf energy that strikes its surface. This, coupled with the long overall signal path, makes it a very marginal mode of communication.

The amateur frequency bands normally used for eme operation, 144, 432, and 1,296MHz, represent a compromise between the overall system noise level, and particularly the receiver noise level, the ability to construct high gain antennas that are not too large, and the ease of generation of sufficient transmitter power. For 144 and 432MHz operation there is a particular problem in the UK, because the output power needed, of the order of 700-800W, requires a special licence from the Home Office for experimental work. This is less of a problem on 1·3GHz because it has been shown that successful communication can be achieved with output powers of only 100W [27]. This is possible because it is practical to build dishes with sufficient gain at this frequency. The essential problems and differences between the three bands when used for eme work are shown in Table 1.

Because of the weak nature of the signal, QSOs tend to be stereotyped and usually consist of an exchange of callsigns, signal reports and "rogers" with many repetitions. Instead of the usual RST report, another system, called TMO, is sometimes used for giving signal reports. These letters are chosen as they consist only of dashes in the morse code and should therefore be more recognizable when signals are down in the noise. As is implied by this, cw is the normal signalling mode although, exceptionally, ssb is possible. Most QSOs are pre-arranged and follow a rigid format that has to be adopted at both ends as in meteor-scatter contacts.

One feature unique to stations with full eme capability is the ability to receive their own "echoes". It takes about 2·5s for the signal to make its way to the moon and back, and this time delay allows the operator to monitor his own test transmissions. This obviously provides a useful check on the satisfactory operation of the equipment.

Because the moon may be moving toward or away from the eme stations at speeds up to 1,500km/h, Doppler shift will change the received frequency. When the moon is rising, doppler effect increases the received frequency; at moonset the frequency is decreased. The amount by which the signal is shifted is linearly dependent on the operating frequency. Thus on 144MHz it is one third of the shift at 432MHz and only one ninth of the shift at 1·3GHz.

In addition to the normal path attenuation, additional problems are caused by *Faraday rotation* of the polarization of the received signal. Because of the reflection of the signal, the polarization sense is reversed on the received signal. A plane-polarized vhf/uhf signal passing through the ionosphere is further rotated, and this happens on both legs of the journey. The net result is a signal arriving at the receiver which may not have the same polarization as the antenna, and this will result in a further signal loss. With antenna systems of fixed polarization such as Yagi arrays, there is nothing that can be done. However, with dish antennas two approaches can be taken to avoid the polarization mismatch; adjust the dish polarization to compensate or use circular polarization at both ends. Where the station at the other end is using fixed polarization, the dish-station operator can rotate the feed horn to adjust the dish polarization to match that of the incoming signal so that maximum signal can be obtained. The higher in frequency eme operation goes, the less is the amount of rotation. Thus the problem is particularly serious on 144MHz operation; the more so since

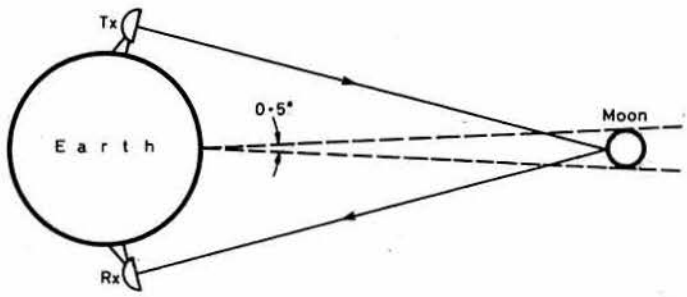

Fig 5. The moon subtends an angle of only 0·5° as viewed from the earth and reflects only about seven per cent of the radio energy that strikes its surface. This, coupled with the long overall signal path, makes it a very marginal mode of communication.

fixed polarization Yagi arrays are generally used for practical reasons. The problem can be overcome with dish systems, since circular polarization can be used and, provided the sense of polarization rotation of the antenna system is that of the received signal, no mismatch and no consequent signal loss occurs. At 1·3GHz, dishes are the most practical antennas and circular polarization is standard.

A third propagation effect on eme communications is that of *libration fading*. This is caused by multiple reflections from the uneven surface of the moon, and also because of the relative movement between the earth and the moon. This gives rise to signal fading due to multipath effects. The depth of this fading can be up to 20dB, and signals are rarely strong enough to be audible in the trough of the fades [27].

A very readable and practical introduction to moonbounce communication can be found in a two-part article by Charles Suckling, G3WDG, starting in the May 1984 issue of *Ham Radio Today*.

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AN IMPROVED Z-MATCH ASTU

(Continued from page 771)

7MHz (and 10MHz if used) the appropriate tap on L3 is selected by S1b. Should it be desired to use an alternative antenna or antennas, fed with coaxial cable, either direct or via the Z-match, this facility is also provided. There is also provision, by S2, to switch the transmitter output direct to a suitable 50Ω dummy load. Once the unit has been set up on each band in turn, and the capacitor dial readings noted on a calibration chart or card which may be affixed to the front panel, switching and re-setting to any desired frequency within the required band is a matter of seconds. The layout is not critical, but it is advisable to mount the coils L1 and L2 with their axes at right-angles to prevent undesirable intercoupling. Also, all earth leads should be as short as possible and the metal front panel should, of course, be earthed. The coupling capacitor, C2, should be mounted on an insulating sub-panel and its shaft fitted with an insulated shaft coupler to isolate it from the front panel and to prevent hand-capacitance effects. When the photograph accompanying this article was taken, the switch S2 and the coaxial output sockets SK2, SK3 and SK4 had not been incorporated into the experimental model. Also, the twin-gang variable capacitor for C2 is unnecessary; a single 500pF maximum capacitor is adequate. The receiving type variable capacitors used in the experimental model Z-match have adequate plate spacing for cw and ssb (peak) output powers of up to 100W. For higher powers it would be necessary to use a transmitter-type split-stator capacitor (or two ganged single-section capacitors) for C1a, C1b. However, C2 requires only receiver-type vane spacing even for high-power operation. Tests with additional feedpoint taps on both L1 and L2 in the modified Z-match circuit showed no practical advantage. However, the tap on the output coupling coil L3 was found to be essential on 7MHz, and would doubtless be required on 10MHz. The very tight coupling between L1/L3 and L2/L4, due to the method of construction used, tends to reduce the operating Q value of the LC circuits and so render them more "tolerant" of the complex reactive loads presented at the input end of the feeder(s) to the antenna(s) used and, incidentally, of frequency excursions within any given band.

Final modified Z-match astu circuit—components list

C1a-1b	Split-stator variable capacitor 20-500pF per section (1)
C2	500pF single-section variable capacitor (shaft insulated)
L1	10t 4cm id c/w 14swg enam copper wire. Tap T1 4t from earth end
L2	5t 4cm id turns spaced wire dia 14swg enam copper wire. T2 1·5t from centre of coil (virtual earth point)
L3	8t 5cm id c/w enam copper wire over L1. T3 at 5t from "earthy" end
L4	3t 5cm id c/w over L2. 14swg enam copper wire
S1	Ceramic wafer switch. All sections single-pole five positions
S2	Ceramic wafer switch, single-pole three positions
SK1-4	Coaxial sockets
F1, 2	Balanced feeder terminals

Notes.

(1) A suitable 250 + 250pF (split-stator or twin-ganged) variable capacitor can be used since the capacity required to tune L1 to 3,500kHz is approximately 420pF, and for 7,100kHz approximately 90pF. If C1a, C1b (paralleled) has a combined minimum capacitance of not more than 20pF, it should be possible also to tune L1 to 10MHz. Otherwise it may be necessary to reduce L1 to nine turns, leaving T1 at four turns from the "earthy" end of L1. A lower minimum capacitance of C1a, C1b as a split-stator capacitor would also be an advantage for the 28-29·7MHz band.
(2) Taps on L1 and L2 soldered to *inside* of coil turn. Tap on L3 soldered to *outside* of coil turn.

Author's note

In the explanation of the way in which the original Z-match astu circuit works, a convenient simplification has been adopted in describing the input circuit function. I am aware of the fact that a more rigorous, mathematical, treatment of the functioning of the input circuitry is possible. However, the practical advantage of the suggested arrangement of "tapping down" the input to L1 and L2 is clearly proven by experimental results obtained. □